THE BASIC MASSIVE ROCKS OF THE LAKE SUPERIOR REGION.

IV. THE PERIPHERAL PHASES OF THE GREAT GABBRO MASS OF NORTHEASTERN MINNESOTA.[1]

A. Introduction.

IN 1886 Professor J. W. Judd[2] described a series of basic rocks from the Inner Hebrides and the adjoining mainland of Scotland and Ireland, that in mineral composition are closely allied to the gabbros with which they are associated. Their structure, however, is quite peculiar. The most notable difference between it and the structure of a normal gabbro lies in the character of the olivine and diallage constituents. These have "more or less rounded outlines, and are imbedded in a plexus of lath-shaped crystals of feldspar; in polarized light these grains are seen not to be parts of one large crystal, but to have very different orientations. The form of the individuals of pyroxene and olivine at once recalls the structure seen in the granulites" (p. 68). It was therefore called by Judd the "granulitic structure." True gabbros, with the granitic structure, were found only in the central portions of great bosses and flows. On the edges of flows and along their upper and lower surfaces the granitic structure gives place to the ophitic or the granulitic structures. The best examples of the last two types were found: the first in dike rocks; the second in lava flows. Hence the conclusion was reached that "the only type of rock absolutely characteristic of intrusive rocks is the granitic; but ophitic varieties and varieties with skeleton crystals in their base abound in, though they are not confined to, intrusive rocks; while rocks of granulitic structure and those with short and rounded microlites in their groundmass are especially abundant among the

[1] Quart. Jour. Geol. Soc., February, 1886, p. 49.

[2] Continued from Vol. I., p. 716.

lavas" (p. 75). The cause of the granulitic structure was thought to be the crystallization of the rock's components during a period before the internal movements of the rock-mass had ceased. The granitic and the ophitic structures occur only in masses of considerable dimensions, where the original molten magma yielding the gabbro or the diabase, existed for some time in a state of perfect internal equilibrium. It is when crystallization goes on in a mass that is in actual motion, or one whose portions are in motion relatively to each other, in consequence of strains set up in the magma, that a granulation of the augite and olivine results.

The rocks so ably described by Judd in the article referred to, have their exact counterparts in northeastern Minnesota. The great mass of the gabbro constituting the "basal flow" in this region has the typical granitic structure. Along its northern edge, however, near the bottom of the mass, occurs a series of rudely bedded rocks, that differ so markedly from the gabbro that they have been regarded as distinct types by most geologists who have seen them in place. Many of them are dense, heavy, vitreous-looking rocks, others are fine-grained, dark gray ones with a sandy texture and often a resinous lustre, while still others have the appearance of a very fresh, brilliant magnetite. Although they mark the northern limit of the gabbro area throughout its entire extent, their best developments are in the neighborhood of Akeley Lake, in Sec. 29, T. 64 N., R. 5 W.; along the north shore of Iron or Mayhew's Lake, in Secs. 29 and 30, T. 65 N., R. 2 W.; and Sec. 36, T. 65 N., R. 3 W.; in the country between Little Sasaganaga and Gabamichigamak Lakes, in the northwest portion of T. 64 N., R. 5. W., and on the north shore of the lake last named, in Secs. 31 and 32, T. 65 N., R. 5 W. In the reports[1] of the Minnesota survey these rocks are called by various names, such as muscovado, quartzite, iron ore, and in the field notebooks of the members of the United States Geological Survey, quartzites, silicified gabbros, etc. The mere recital of these names is enough to

[1] 15th Ann. Rept., pp. 183, 351, etc. 16th Rept., p. 355, etc.

suggest the obscure relationships of the rocks designated by them.

A rapid glance at the sections of the rocks composing the beds indicates that they may be separated into three classes, of which one, the non-feldspathic gabbros, corresponds to the peridotites[1] associated with the Scottish gabbros. The other two classes embrace granulitic rocks whose structure is similar in all essential respects to the structure of the Scottish rocks referred to above.

The members of one of these two classes are granulitic gabbros, corresponding in their important features with the granulitic gabbros of Professor Judd. The other class of granulitic rocks comprehends a series of quartzose members, composed of quartz and olivine, of quartz and hypersthene, or of the three minerals mentioned. The quartz is evidently not secondary, for the olivine associated with it is almost entirely unaltered in many cases. It has crystallized in its present position, and in most specimens after the olivine was formed. It has been suggested that these peculiar rocks were originally quartzites that have been altered by the great gabbro mass south of them. Many of them appear to have had this origin. They are probably metamorphosed sediments, but of such a unique character that a critical study of them is demanded before a positive decision as to their genesis can be given.

The present communication deals only with the basic and the granulitic gabbros, rocks that are unquestionably phases of the normal gabbro.

B. The Non-Feldspathic Gabbros (Peridotites).

In choosing the group name "non-feldspathic gabbros" for these rocks, in preference to the more usual one "peridotites," emphasis is placed on the fact that the rocks included under it are nothing more nor less than gabbros in which feldspar is lacking. The magma which gave rise to them was undoubtedly a portion of that which, under the ordinary circumstances

[1] J. W. JUDD: Quart. Jour. Geol. Soc :Vol. 41, 1885, p. 357.

prevailing during the period of its cooling, produced the coarse-grained gabbro that covers so many hundreds of miles in northeastern Minnesota. Under certain conditions this same magma yielded the very basic rocks here described, but these form such a small mass as compared with that of the great gabbro, that it does not seem wise to designate them by any name that will not at once indicate their very close relationship to the gabbro. Peridotite as the name of a group of rocks produced by the slow cooling of a very basic magma is well enough, but as a name for the aggregation of basic minerals from a comparatively acid gabbro magma it would be as much out of place as the use of the same name for the olivine-diallage concretions of a basalt.

The rocks of this class occur, as has been said, along the north boundary of the gabbro area, where they are found alternating with the granulitic gabbros of the several varieties. The thickness of the bands ranges from twenty or more feet down to a fraction of an inch only. In a single thin section may sometimes be discovered several of them. The line of separation between the bands is nowhere very distinct, and in the thin section it is seen to be quite gradual. Many times the rocks are so charged with magnetite as to have suggested their being worked for ore. Professor N. H. Winchell,[1] in his discussion of the iron ores of Minnesota, classes this magnetite with that occurring in the normal gabbro under the group name "gabbro-titanic-iron group." The difference between the magnetite of the quartzose beds under the gabbro and of the basic rocks associated with the gabbro is recognized.

A specimen of one of the basic rocks was submitted to Dr. Hensoldt[2] for microscopic study. In the section examined basic and acid bands occur alternately. The basic portion of the rock (M. 1339), which is from the Akeley Lake region, is described as a compact lherzolite, chiefly composed of yellowish-

[1] The Iron Ores of Minnesota, Bull. No. 6, Geol. and Nat. Hist. Survey of Minn., pp. 123–126.

[2] Ib., p. 127.

green enstatite, olivine and magnetite. "Even in the same hand specimen it passes from a fine schistose condition into a coarse crystalline one, while in some of its modifications it assumes the character of a regular quartzite." The schistose portion "shows an admixture of well-defined tabular plates of yellowish-green enstatite, and granular or 'fractured' olivine of a paler shade. The enstatite exhibits an exceedingly fine striation, and it contains no enclosures, except a few grains of magnetite. It polarizes brilliantly, but shows no pleochroism. The olivine is more abundant than the pyroxene. It is present in the form of angular masses and grains, which have a fragmental appearance as if crushed by mechanical pressure or in consequence of a sudden thermal disturbance. The magnetite occurs in rounded grains and crystals, varying from dust-like minuteness to aggregates equaling in size the largest of the enstatite tablets."

Titaniferous Magnetites.—The specimens in the possession of the United States Geological Survey all contain a large proportion of magnetite, which in some cases runs so high as to constitute 90 per cent. of the entire rock. These latter rocks have the bright metallic lustre of magnetite and usually a finely granular texture. The lustre frequently becomes very brilliant and the specimen takes on the peculiar pinkish tinge of ilmenite. A careful inspection of such specimens as seem to be pure ore, reveals the presence in them of tiny yellowish green grains of olivine, but these are so rare that they produce but little impression on the general aspect of the rock. When the magnetite makes up practically its entire body, the rock is much jointed, and, consequently, it easily breaks into small irregular or cuboidal fragments, as Winchell has already noted, and these are not unfrequently natural magnets. Tests of magnetites of this kind from the shores of Little Sasaganaga Lake, N.W. ¼ Sec. 7, T. 64 N., R. 5 W., prove them to be very rich in titanium, as was surmised from their pinkish tinge.

Professor Winchell[1] cites several analyses of titaniferous magnetites from the north edge of the gabbro area, that show from 2.23

[1] Bull. No. 6, Minn. Geol. Survey, p. 141.

per cent. to 16.03 per cent. of TiO_2. He gives no account of their associations, but refers to them simply as gabbro-magnetites. In the same group he includes the magnetite occurring as sand on Black Beach, near Beaver Bay. The rock of Beaver Bay is, however, not a portion of the great gabbro mass that we are now discussing, but it is probably a portion of a sheet or "sill" intrusive in the Keweenawan strata, and occurring at a much higher horizon than that at which the rock which is the subject of the present series of papers, occurs.

Olivine-Pyroxene Aggregates.—When magnetite is scarce in the basal beds of the gabbro, the rocks are usually very fine-grained, sugary aggregates of yellowish green olivine, and a dark brilliant substance that upon examination is found to be a pyroxene. Occasionally a large plate of pyroxene or of hornblende is imbedded in the fine aggregate, but this so rarely happens that it does not affect the general appearance of the rocks. On the other hand it is not uncommon to find in what is apparently a fine-grained mass many large areas of irregular shapes that reflect light uniformly. These evenly reflecting surfaces are the cleavage faces of large grains of pyroxene or of amphibole that are so completely saturated with inclusions as to appear as heterogeneous in structure as the aggregate in which they lie. The entire fracture surface of specimen M. 453H, for instance, is made up of interlocking areas with evenly reflecting surfaces, each covering about a sixteenth of a square inch, and yet so full of little inclusions are they that the rock must be described as possessing a finely granular texture. In very rare cases the thinner bands are very coarsely granular, when they consist almost exclusively of pyroxene with now and then a little magnetite. In all cases the structure is obscurely schistose, and large pieces tend to break more easily along their bedding planes than transversely thereto.

In the most olivinitic phases of these rocks olivine comprises nearly their entire mass. The mineral .here occurs in irregular interlocking grains of a pale yellowish green color, crossed by cracks and fissures in which a little limonite or other brown iron

hydroxide has separated. Its inclusions are not abundant. A few tiny grains of plagioclase, a rounded grain of quartz and an occasional mass of leucoxene or flake of pyroxene, besides small irregular grains of magnetite are the only ones noticed.

Here and there, between the olivines, is a plate of pink augite, which is slightly pleochroic and which in most of its characteristics approaches the diallage of the normal gabbro, except that it never contains the gabbroitic inclusions. Its outlines are irregular and its contours are moulded by those of the olivine, so that it is undoubtedly younger than this component. Locally the diallage has acquired a fibrous structure due to alteration into a very pale yellow or colorless mineral supposed to be tremolite (or actinolite).

Most of the latter substance forms groups of fibres, whose relation to the augite can be inferred only from the fact that they occur between the olivine grains, with the contacts between the two minerals quite sharp. The olivine has undergone little, if any, decomposition, so that the fibres must be due to the alteration of the pyroxene, if they are secondary rather than primary in origin. The little groups or bundles of these fibres are very compact except at their ends, where they are frayed out into single fibres whose extinction is sometimes parallel to their long axes, and sometimes is slightly inclined to them. Their double refraction is strong and their polarization colors are brilliant. The axis of least elasticity is nearly parallel to the longitudinal direction of the needles, which are therefore negative, if the orientation of the optical axes is as it is in normal hornblende. Two cleavages are discernible, one parallel to the long axes of the needles and one (a parting) transverse to them. Cross sections of the bundles were not seen, so that it is impossible to say positively that the mineral is a hornblende, but its similarity to certain fibres in other rocks,[1] that are certainly hornblende, is so strong that there can be little question that these are hornblende as well.

[1] Cf. description of actinolite in actinolite-magnetite schists, Amer. Jour. Sci., XLVI., 1893, p. 176.

As to the origin of the supposed tremolite there is a doubt. The assumption of fibrosity by the diallage in some cases, would seem to point to a secondary origin for the bundles of hornblende since this is the only fibrous mineral in the rock. The little bundles, however, are so compact and their situation within the thin section is so remote from that of the diallage that the supposition of a primary origin for them seems to be demanded.

The magnetite, which is much more abundant in these rocks than in the normal gabbro, occurs as inclusions in all their constituents. It is more commonly an attendant of the tremolite, however, than of either the diallage or the olivine. It occurs as small irregular grains between the fibres of the bundles and in the exterior portions of the fibrous groups, and in nearly all cases the longer directions of the grains are parallel to the long axes of the fibres.

In mineral composition these rocks are wehrlites, but their structure is quite different from that of any rocks of this character heretofore described. The diallage and tremolite act as interstitial substances inclosing olivine grains, where the first two minerals are in sufficient quantity to serve this purpose. Where they are absent the rock consists entirely of a mosaic of interlocking grains of perfectly fresh olivine. Since both the olivine and the diallage are identical in characteristics with the same minerals in the normal gabbro, we are led to suspect that the rock is a special phase of the latter, in which the acid constituent — plagioclase — is lacking.

Pyroxene Aggregates.— In other beds the olivine is in less quantity than in those just described, and the rock composing them is slightly different. The olivine is in the same small grains, but these no longer form mosaics. They are in greater part included within large irregular plates of green pyroxene, whose ragged edges extend out for some distance between other surrounding olivine grains. The material of the plates is bright green in color, and it is slightly pleochroic. Its highest observed extinction is 36°, and its most common inclusions are grains of magnetite and masses of limonite. Most of the magnetite is

between the olivine grains and the pyroxene, or in the interstices between the plates of the latter mineral, though some large grains are included within the olivine.

In the non-olivinitic types of these basic rocks, pyroxene and magnetite are the principal components. These types are perhaps more common than the olivinitic types, but their variety is so great that a description of them would be little else than a description of individual specimens. Pyroxene forms the greater part of all these rocks, but the character of the pyroxene changes for each individual bed, so that it is impossible to classify their material with any degree of success. It must therefore suffice to study one of the most striking types, and to leave the others with the statement that they are composed exclusively of some form of pyroxene and of magnetite.

The most interesting of the pyroxene-magnetite rocks is that already referred to as exhibiting lustre-mottling (M. 453 H). In this the pyroxene is present in two forms. It occurs as large, strongly pleochroic green plates, and as small, slightly pleochroic green grains, the latter included in the former. The lustre mottling on the hand specimen is due to the reflection from the large plates, and the fine-grained texture of the rock is the result of the uniform distribution of the small grains within the larger ones. The entire area of a slide is often occupied by four or five of the pleochroic plates, with their inclusions. They interlock with irregular sutures, and thus completely cover the thin section. When examined over the lower nicol the plates are yellowish-pink transverse to their prominent single cleavage and light green parallel to this. The axis of least elasticity in sections showing parallel cleavage lines is in the direction of this cleavage, and the extinction is consequently also parallel thereto. In cross sections the pyroxene cleavage is plainly apparent. Here the pleochroism is in yellowish pink and light wine-yellow tints, the latter in the direction of the smaller of the two lateral axes of elasticity. The absorption is consequently $\mathfrak{c}$=green$>\mathfrak{a}$=yellowish pink$>\mathfrak{b}$=wine yellow. The mineral is in all probability hypersthene.

The small grains included within the hypersthene are bright green in all positions. Now and then slight changes in the shade are noticed, indicating very weak pleochroism. The color is so nearly like that of the green ray of the hypersthene, that the presence of the grains in the latter mineral can be detected only with the greatest difficulty, when the slide is in such a position that the parallel cleavage of this mineral runs in the direction of the vibration plane of the lower nicol. In most of the included grains a well-marked coarse cleavage is noticed, the maxium extinction against which is 41°. In addition to the coarse cleavage there is often observed a second and finer series of cleavage lines, whose direction is parallel to that of the coarser ones. The properties of this pyroxene are those of diallage.

The magnetite in this rock is very abundant. It is in large and small grains imbedded in the pyroxenes, the larger ones usually in the hypersthene and the smaller ones in the diallage. Many of the grains are irregular in shape, but quite a number show crystal forms. There is no evidence that any of the mineral is of secondary origin. It all seems to be original. A portion of the magnetite separated from the powdered rock by digestion with hydrochloric acid was tested for titanium with a negative result, although specimens from other similar rocks contain this element.

The only other constituent observed in the section was a bright green hornblende, whose extinction is not known to be greater than 13°. It occurs in but a few flakes with irregular and indefinite outlines that fade off into the surrounding pyroxenes. It is probably secondary.

A comparison of the descriptions of the types of rocks above given indicates that the hypersthene in the last described type has taken the place of the olivine in the others. The green diallage in both cases is the same, though in the first two instances it surrounds the olivine, *i. e.*, it is younger than this mineral, while in the other instance it is surrounded by the hypersthene —it is older than the latter. A study of the granulitic phases

of the gabbro points to the same conclusion, viz., that the hypersthene and olivine occupy similar places in the rock's constitution. Where the one is present the other is usually absent. They seem to be complementary components. It is also noticeable that when hypersthene is present and olivine absent the rock contains more magnetite than in the case where the conditions are reversed.

In some of the beds the percentage of the iron oxide increases as has already been said, until it reaches 80 per cent. or even 95 per cent. of the rock mass. In some of the sections made from these rocks nearly the entire field of the microscope may be occupied by a single mass of compact magnetite. On its edges this mass often breaks up into small grains that are cemented together by a large plate of green pyroxene. This observation is valuable as showing that the beds composed almost exclusively of magnetite have the same origin as those in which this mineral constitutes only a small part of the rock mass. The latter are certainly phases of the gabbro, hence the former must also be phases of the same rock. Whether most of the magnetite in these varieties is primary or secondary cannot be told. Much of it is certainly primary.

Granulitic Pyroxene Rock.—An interesting variety of the basic rocks is No. M. 1334. It is slightly schistose, and is composed almost exclusively of colorless pyroxene and green hornblende, in small grains with rounded contours. Its structure is granulitic. A brief description of the rock is given in the chapter on the granulitic gabbros.

The Relation of the Basic Rocks to the Normal Gabbro.—From the descriptions that have preceded, it is seen that the basic rocks along the northern periphery of the gabbro are composed almost exclusively of the more basic constituents of the normal rock—viz., magnetite, olivine, and pyroxene. The feldspar of the main mass of the gabbro is entirely lacking in them. The accumulation of the basic portions of the gabbro-magma on its periphery may be accounted for by its differentiation during cooling. Such a differentiation of a gabbro-magma

has been described a number of times. Matthew[1] has noted it in a gabbro area near St. Johns, New Brunswick, while Vogt[2] has described it at a large number of places in Norway, Sweden, and other European countries. A notable feature in connection with the phenomena described by Vogt is the association of oxide and sulphide ores with the basic portions of the differentiated rocks. Many of the magnetite deposits of Norway are shown by this author to be peripheral phases of gabbro. The occurrence in Minnesota is similar to the Norwegian occurrences, and hence the author concludes that the ores of Winchell's "gabbro-titanic-iron group" have a similar origin. It has been shown by the descriptions that this is the case; the basic aggregates on the northern border of the gabbro area are peripheral phases of the coarse-grained olivine gabbro, whose composition and structure are so uniform throughout most of its extent, and the ores associated with these aggregates are only more basic phases of the same magma, by whose differentiation, after its intrusion into its present position, olivine gabbro, pyroxene-olivine aggregates, and almost pure titaniferous magnetite beds were formed.

W. S. BAYLEY.

[1] W. D. MATTHEW: Trans. N. Y. Acad. Sci.

[2] J. H. L. VOGT: Bildung von Erzlagerstätten durch Differentiationsprocesse in basischen Eruptivmagmata. Zeits. f. prakt. Geologie, Januar, 1893.

(To be concluded.)